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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

No. 1268

AN APPLICATION OF STATISTICAL DATA IN THE DEVELOPMENT OF GUST-LOAD CRITERIONS

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SUMMARY

In conjunction with assumptions concerning the proportion of time spent at various speeds, statistical gust data were used to determine gust load factors that could be exceeded a given number of times during the operational life of an airplane. The results indicated that present gust load factors might be considerably lowered in certain cases with a consequent decrease in structural weight. Modification of the present criterion, however, must await the accumulation of data not presently available.

INTRODUCTION

Structural design requirements for airplanes commonly include the determination of gust load factors, which are based on the combination of certain effective gust velocities with arbitrarily chosen design speeds. Although the currently used design gust velocity of 30 feet per second has proved to be reasonably conservative when applied in the neighborhood of the design high speed, the degree of conservatism, as well as the choice of a suitable value of design gust velocity for application at other speeds, has frequently been the subject of controversy. The controversy has resulted both from a lack of statistical data sufficiently extensive to permit the accurate determination of the probability of failure for any assumed set of conditions and from the fact that a reasonable value for the probability of failure has never been specified.

The determination of the life expectancy of an airplane requires a knowledge of the frequency of occurrence of atmospheric gusts in combination with a knowledge of the time spent at various airspeeds (speed-time distribution). Although average gust frequency has been reasonably well determined and reported in reference 1, data on speed-time distribution are completely lacking. Despite this lack of data, however, it is possible (1) to assume reasonable or limiting values of various parameters that relate to speed, speed-time distribution, permissible number of times that a given load can be exceeded during the operational life of an airplane, wing loading, and airplane and operating conditions, and (2) to apply the assumed values to representative cases to determine whether present requirements give answers that appear reasonable.

As the result of such an analysis, the present paper shows the influence of operational speed, airplane life, speed-time distribution, and wing loading on airplane life expectancy and indicates possible extreme cases for which present design requirements are inadequate or unreasonable.

SYMBOLS

U_{eff}	effective gust velocity, feet per second
W	gross weight of airplane, pounds
S	wing area, square feet
W/S	wing loading, pounds per square foot
ρ_0	mass density of air at sea level, slugs per cubic foot
V_e	equivalent airspeed, miles per hour
V_G	maximum equivalent permissible gliding or diving speed, miles per hour
V_L	maximum equivalent airspeed in level flight, miles per hour
L	airplane operational life, miles
f_r	speed distribution, ratio of miles flown in each airspeed bracket to total number of miles flown
$\bar{c}$	mean geometric wing chord, feet
d	number of allowable critical gusts in each airspeed bracket (A critical gust is a gust that results in a load equal to or exceeding the design applied load for the airplane.)
K	relative alleviation factor (reference 1)

m slope of wing lift curve corrected for aspect ratio, per radian

n airplane load factor, g units

Δn increment of load factor, g units

Δn_L increment of load factor resulting from a 30-foot-per-second gust acting at V_L

λ_{cr} spacing of critical gusts for airplane with mean geometric wing chord of 1 foot (The mean distance along a flight path between critical gusts for any airplane is then $\lambda_{cr}\bar{c}$.)

w airplane gust parameter, acceleration in g units per unit gust

$$\left(w = \frac{1.47\rho_0 mKV_eS}{2W} = \frac{\Delta n}{U_{eff}}\right)$$

M Mach number

$C_{N_{max}}$ maximum normal-force coefficient

INFORMATION REQUIRED

Before an analysis can be made to determine the design load factor, it will be necessary to know, or to be able to assume, the spacing of critical gusts λ_{cr}, the speed distribution in terms of V_e and f_r, the number of allowable critical gusts d, and the airplane operational life L.

Spacing of critical gusts.- In order to determine the spacing of critical gusts, it is necessary to know either the actual frequency distribution of gust intensity or the relative frequency distribution of gust intensity in combination with a number that expresses the average number of gusts that will be experienced per mile of flight. At the present time, the only available data have been summarized in reference 1, in which the relative distribution of effective gust velocity has been shown to be essentially independent of terrain, altitude, airplane size, and airplane characteristics; as a result, two limiting unit summation curves of effective gust velocities were presented. These curves are reproduced herein as figure 1. Curve A indicates a more frequent occurrence of large gusts than curve B; hence, in the interests of conservatism, curve A was selected as the basis for the following analysis.

The analysis of total gust frequency given in reference 1 shows that the total gust frequency per operating mile depends largely on the terrain and on the operational altitude and is inversely proportional to the mean geometric wing chord. For average airline operating conditions approximately five significant gusts per mile will be experienced by an airplane with a mean geometric wing chord of 10 feet; hence, the total frequency can be expressed as $50/\bar{c}$ gusts per operating mile.

Curve A of figure 1 and the total gust frequency per operating mile can now be combined to obtain a general curve of the average number of miles that must be flown to encounter one gust equal to or greater than a given intensity. The result is shown in figure 2, which includes the occurrence of both positive and negative gusts, and is based on a value for $\bar{c}$ of 1 foot. In order to apply this curve to any airplane, it is necessary only to multiply the ordinate (spacing of critical gusts per mile) by the mean geometric wing chord.

Speed distribution.- Inasmuch as airplanes generally fly at speeds that are highly variable, it is necessary to define the frequency distribution of speed in terms of percent of total flight miles spent in different classifications of indicated airspeed. Statistical data of this kind are currently lacking; nevertheless, it is possible to make reasonable assumptions regarding the speed distribution and to show the effect of varying such assumptions.

Number of critical gusts.- Selection of the total number of critical gusts that can be permitted during the operational life of an airplane is largely a matter of judgement. In view of the current use of multiplying factors of safety, it appears reasonable to assume that more than one critical gust can be permitted; on the other hand, the degree of conservatism of the airplane design is decreased as the number of critical gusts increases.

Operational life.- The operational life of the airplane is defined as the average number of miles that the airplane must fly before its structural integrity can be questioned. This definition should not be construed to mean that the (static) structural strength of the airplane is decreased as a result of the repeated loads to which it is subjected; it means, rather, that experience shows that the V-G diagram continually grows as the number of miles flown increases. The structural life will depend on both the airplane type and the airplane mission - a fighter airplane in combat service will require only a short operational life as compared with a [illegible] airplane.

METHOD OF ANALYSIS

Given the foregoing information, the analysis is carried out as follows:

(1) The spacing of critical gusts in each speed classification, in miles, is obtained by substitution of appropriate values in the formula

$$\lambda_{cr} = \frac{Lf_r}{d\bar{c}}$$

(Note that $\bar{c}$ has been included in this formula to reduce the case to that of an airplane with a mean geometric wing chord of 1 foot.)

(2) From figure 2, with values of λ_{cr} known, the corresponding values of effective gust velocity U_{eff} can be obtained. If the value of U_{eff} and the airspeed corresponding to each speed classification are known, the increment of gust load factor for each speed classification can be obtained by substitution in the usual gust formula

$$\Delta n = \frac{1.47\rho_0 mKU_{eff}V_e S}{2W} \qquad (1)$$

The points thus obtained may be plotted on the V-n diagram for the airplane under consideration. (When applying the usual Glauert compressibility correction as in the case of the high-speed fighter-type airplane considered subsequently, replace m by $m/\sqrt{1 - M^2}$, where M is the Mach number for the altitude under consideration.)

EXAMPLES

Since airplanes according to their intended use are usually divided into classes for purposes of structural design and the limit maneuver factors are specified accordingly, the results of the analysis will obviously be affected by the intended use of the airplane. For the present paper, therefore, calculations were made for various values of airplane operational life and speed distribution for a high-speed fighter-type airplane (limit positive maneuver load factor of 8.0), for a light bomber-type airplane (limit positive maneuver load factor of 3.67), and for a large transport-type airplane (limit positive maneuver load factor of 2.5). These examples were selected to give two extreme cases and one intermediate case.

For all examples, certain assumptions have been made to supply the lacking data and to simplify the estimates of speed-time distribution and number of critical gusts. Three speeds have been assumed as follows: $0.8V_L$, V_L, and V_G. The airplane will be assumed to spend its entire life only at these three speeds. Since it appears probable that flying speed will generally be reduced below $0.8V_L$ during periods of turbulence and since such reduction will result in lowered load factors for a given value of U_{eff}, this assumption will be conservative. The total number of critical gusts that can be permitted during the life of an airplane has been arbitrarily set at 15. This value is not believed to be unreasonably low, yet it avoids any necessity for considering the possibility of fatigue failure. In order to equalize the chances of failure, this total number of critical gusts is evenly distributed among the three speeds; five critical gusts are hence permitted at each speed.

<u>High-speed fighter-type airplane</u>.- A hypothetical high-speed fighter-type airplane was assumed, of which the pertinent dimensions and performance characteristics are given in table I. In the construction of the V-n diagram given in figure 3, a 30-foot-per-second gust was assumed for all speeds up to V_G; in addition, the usual Glauert compressibility factor was applied to the slope of the lift curve, with operation at sea level assumed. No correction was applied for change in airplane attitude because the airplane was assumed to be sufficiently clean to approach V_G in a relatively shallow dive.

The conditions assumed are given in table I and consist of two values of airplane life of 1,000,000 and 500,000 miles and two assumed speed-distribution patterns. The values for airplane life have been intentionally selected to be conservative; the higher value, however, which corresponds to 6 flying hours per day at 360 miles per hour for a period of 15 months, is believed to be excessive. It will be noted that the speed-distribution patterns are essentially alike except that the proportion of flying miles spent at the higher speeds has been increased for condition II. The values of load factor obtained are plotted in figure 3 and are joined by straight lines to facilitate their study.

<u>Light bomber-type airplane</u>.- A light bomber-type airplane has been chosen that is similar to some now in military service.

The pertinent dimensions and performance characteristics are given in table II. In the construction of the V-n diagram given in figure 4, a 30-foot-per-second gust was assumed for all speeds up to V_G, compressibility effects being neglected. The V-n diagram is made for two values of wing loading in order to show the effect of this parameter. It will be noted that the gust load factor is critical only for the light wing loading.

The conditions assumed are given in table II and consist of two values of airplane life of 1,000,000 and 5,000,000 miles, of two wing loadings, and of two speed distributions. The lesser of the two assumed values of airplane life is considered to be reasonable for this type of airplane; the higher value, which corresponds to 10 years of daily operation at $0.8V_L$ for 7 hours per day, is included to show the effect of a radical change in operating life on the gust load factor. The two speed distributions were selected because under combat conditions a higher proportion of time is expected to be spent at V_L. The values of load factor obtained are shown in figure 4 and are joined by straight lines to facilitate their study.

Large transport-type airplane.- A large transport-type airplane that is reasonably representative of present-day designs was assumed. Pertinent dimensions and performance characteristics are given in table III. In the construction of the V-n diagram shown in figure 5, a 30-foot-per-second gust was assumed for all speeds up to V_L, after which the gust was assumed to decrease linearly to 15 feet per second at V_G. No correction for compressibility was applied in this case.

The conditions assumed are given in table III and consist of two values of airplane life of 5,000,000 miles and 15,000,000 miles and of three speed distributions. The lesser of these two values of airplane life is believed to be somewhat low in view of present utilization trends; this value corresponds to operation for 12 hours per day for approximately $6\frac{1}{2}$ years at an average speed of 180 miles per hour. The greater of these two values is distinctly conservative and, for the same utilization and average speed, amounts to approximately 19 years of operation. The speed distributions have been selected to represent two extreme cases and one intermediate case. For one extreme case, the airplane is considered to spend 24 percent of its operational life at V_L; for the other extreme case, the airplane is considered to spend only 5 percent of its operational life at V_L. The intermediate case is considered to be more nearly representative of actual conditions. For all cases, it is assumed that the airplane will spend 1 percent of its lifetime at V_G. This assumption is highly conservative, as unpublished V-G data for transports indicate that, although V_L may sometimes be considerably exceeded, the attainment of a speed in excess of V_G is an extremely rare occurrence. The values of load factor obtained are shown in figure 5 and are joined by straight lines to facilitate their study.

DISCUSSION

The discussion that follows is divided into three parts. The first part deals with the general implications and relations of the analysis; the second part discusses the results obtained by the specific examples; the third part discusses possible sources of inconsistency between results of the analysis and future measurements, as well as certain limitations of the analysis.

General

Average number of miles per critical gust.- The value of λ_{cr} is based on the assumption that it will be applied to a large number of airplanes flying a large number of miles. In other words, given a large number of airplanes, all of which have flown the same distance, it is possible that some of the airplanes may never encounter the predicted number of critical gusts whereas others may encounter several times the predicted number. Nonetheless, the average for all airplanes will approach the predicted value.

Distribution of total number of critical gusts.- The procedure used herein has been to distribute the total number of gusts equally among all speed brackets and thus to specify that the probability of failure be the same for all speeds. An alternative method might be to distribute the total number of critical gusts in proportion to the number of miles flown in each speed bracket; this method has not been used, however, as this procedure would be tantamount to requiring that the higher the speed, the safer the airplane.

Increasing the number of speed brackets and thus decreasing the number of miles flown in each speed bracket makes λ_{cr} approach a limiting value since the total number of critical gusts is constant; hence, developing a continuous V-n envelope is possible for the entire speed range from the cut-off imposed by $C_{N_{max}}$ to V_G. The actual speed distribution would have to be precisely known, however, before such an envelope could be more than approximated.

Effect of speed distribution.- The effect of a change in speed distribution can readily be determined by reference to figure 6, which was obtained from figure 2 by means of the relation

$$\Delta n = wU_{eff} = w\ f(\lambda_{cr})$$

where $f(\lambda_{cr})$ is a function expressing the relation between U_{eff} and λ_{cr}. At a constant speed (constant w) the magnitude of the effect of a change in speed distribution is readily seen to be a function of λ_{cr}. Over the range from $\lambda_{cr} = 10$ to $\lambda_{cr} = 100,000$, however, a tenfold increase in λ_{cr} for any value of w will only increase Δn by a value from 27 percent to 36 percent. The speed distribution, therefore, need not be known with exactitude. Conversely, slight changes in Δn will result in large changes of operational life.

Comparison with current criterion.- The question may be raised as to whether the analysis will show a larger or a smaller load factor than the current gust-load criterion. For the case of an airplane designed for a 30-foot-per-second gust at V_L and with compressibility effects neglected, the following relationship will hold:

$$\frac{\Delta n}{\Delta n_L} = \frac{U_{eff}V_e}{30V_L} = \frac{f(\lambda_{cr})V_e}{30V_L}$$

where Δn_L is the increment of load factor resulting from a 30-foot-per-second gust acting at V_L. This relationship is shown in figure 7 for three values of $\Delta n/\Delta n_L$.

Examination of figure 7 indicates that, in terms of the analysis previously presented herein, the current gust-load criterion appears to yield reasonable values of operational life, particularly in view of the probability of reduction in speed during periods of severe turbulence.

Effect of changes in speed on spacing of critical gusts.- The effect of a change in speed on the spacing of critical gusts will depend on whether that spacing is referred to limit load factor or to ultimate load factor. If λ_{cr} refers to limit load factor, the effect may then be determined for the generalized case by reference to figure 6. The change in λ_{cr} for a given change in w is a function of Δn and decreases as Δn decreases. This application is equivalent to stating that as the required load factor decreases the effect on λ_{cr} of a change in speed likewise decreases. For the special case of an airplane that is initially designed for a

30-foot-per-second gust at V_L, reference may be made to figure 7, in which it will be noted that reducing the speed from V_L to $0.8V_L$ increases the operational life by a factor of 5.5, whereas reducing the speed to $0.667V_L$ increases the operational life by a factor of 24.

A different situation exists when the spacing of critical gusts is referred to the ultimate load factor, as the ultimate load factor is currently determined by applying a multiplying factor to the limit load factor - not to the increment of load factor. As a result, the values of λ_{cr} for ultimate load factor will depend on the value of Δn_L and on the direction (positive or negative) of the gust. In order to show the magnitude of this effect, the values given in table IV have been computed for an airplane designed for a 30-foot-per-second gust at V_L and for $\Delta n_L = 2.0$ by extrapolation of the straight-line relation for $U_{eff} \rightarrow 25$ feet per second given in figure 2. These values, when multiplied by 10, may be considered typical for an airplane of the DC-3 class.

The results given in the last two columns of table IV are of particular interest in regard to the probability of complete structural failure. The significant difference between critical gust spacing for positive ultimate load factor λ_{cr_p} and critical gust spacing for negative ultimate load factor λ_{cr_n} indicates the illogicality of current use of the ultimate factor of safety, as the chances of complete structural failure are from 50 to 400 times as great for negative gusts as for positive gusts. This illogicality is pointed out even more forcefully by comparing columns 2 and 4, whereby it will be noted that the ratio of λ_{cr_n} to $\frac{\lambda_{cr}}{2}$ varies from 15 to 30. This ratio implies that, on the average, if an airplane encounters from 15 to 30 negative gusts of sufficient magnitude to exceed the limit load factor, one of the gusts will exceed negative ultimate load factor.

Examples

<u>High-speed fighter-type airplane</u>.- A question that may legitimately be raised concerns the propriety of applying gust-frequency data obtained during regularly scheduled transport operations to the design of specialized military airplanes. Reference 1 shows that relative frequency distribution of effective gust velocity is substantially unaffected by terrain, altitude, airplane size, and airplane characteristics; hence any errors that may arise in the

application of the data of reference 1 to military airplanes will concern only the frequency of gusts per mile of flight. Although no specific information on this subject is available, it appears reasonable to assume that military airplanes, especially of the fighter type, will not generally encounter gust frequencies so high as $50/\bar{c}$ gusts per mile. The use of transport operational data would therefore appear to be conservative; the degree of conservatism is not thought to be excessive in view of the relatively slight change in U_{eff} that will be obtained by a large change in λ_{cr}.

Reference to figure 3 shows that the effect on load factor of a change in speed distribution is small. If the time spent at V_G is multiplied by 2.5, the load factor will be increased by only about six-tenths of a load factor, or about 12 percent for the worst case (negative gust). Such a result would be expected as, not only will most of the airplane life be spent in the lowest speed bracket, but also a large change in λ_{cr} will not seriously affect U_{eff}. Errors as large as 100 to 200 percent can apparently be tolerated in estimating the proper values of Lf_r for the higher speeds (V_L and V_G).

Inspection of figure 3 shows that the application of a 30-foot-per-second gust at V_G, in combination with a compressibility correction, results in a positive limit gust load factor greater than 10.5. The results of the analysis, on the other hand, indicate that only positive maneuvering loads are critical for design, although negative gust loads are still critical at V_G. Hence, in regard to the design of high-speed airplanes for which a 30-foot-per-second gust may be assumed to act in conjunction with speeds up to V_G, the analysis indicates that the present criterion is highly conservative. Such excessive conservatism may easily result in severe weight penalties that are unnecessary to preserve the structural integrity of the airplane; in the specific case presented, considerations of life expectancy would probably reduce the airplane structural weight by an amount from 400 to 800 pounds.

<u>Light bomber-type airplane</u>.- The effect on load factor of a change in speed distribution is again seen to be relatively small (fig.4). The effect of an extreme change in operational life (by a factor of 5) is seen to outweigh considerably the effect of a changed speed distribution; even this effect, however, is not excessive.

The analysis indicates that for a wing loading of 44 pounds per square foot, the maneuver loads are critical for design. If the airplane is initially designed for a wing loading of 22 pounds per square foot, however, considerations of life expectancy show a potential reduction in gust load factor to the point at which only maneuvering loads are critical in design. It should be noted, moreover, that the airplane with a wing loading of 22 pounds per square foot can be considered equivalent to the heavier airplane at reduced gross weight; hence considerations of life expectancy may be used to reduce local load factors, such as those applied to engine nacelles and supports.

Large transport-type airplane.- Since transport-type airplanes are designed to low maneuvering load factors as compared with present military airplanes, the effect on load factor of a change in speed distribution can be expected to be relatively greater. Even in the present case, however, the change does not appear to be excessive. For example, figure 5 shows that if the time spent at V_L (conditions X and XI) is multiplied by a factor of nearly 5, the change in load factor is about 0.36n. Multiplying the operational life by a factor of 3 has nearly the same effect (conditions VIII and IX); that is, the maximum load factors are increased by about three-tenths of a load factor.

The analysis shows an increase in the gust load factor at V_G. Such an increase might result in increased structural weight; the magnitude of weight increase would depend on the specific airplane characteristics and design and is hence not further discussed. The load factors at V_G, however, can be reduced by reducing the relative proportion of time spent at that speed, provided experimental evidence warrants it. With regard to the fact that the current civil gust design criterion specifies that U_{eff} be 15 feet per second at V_G, figure 2 shows that f_r would have to be changed from 0.01 to 0.0006 to become equivalent to the present criterion. Unpublished data from the analysis of V-G records show that the proportion of time spent at speeds in excess of V_L is extremely variable and depends, among other things, upon the type of airplane and upon the operator. As previously mentioned, for an airplane to attain V_G is extremely rare during domestic transport operations; however, further statistical data are required to permit the assignment of a proper value to f_r for V_G or to determine an intermediate speed between V_L and V_G. In the analysis, moreover, the probability of encountering a gust of a given magnitude has been assumed to be the same whatever the airplane speed; that is, the curve of figure 2 may be applied to any classification of airspeed. This assumption implies that the transport pilot makes no attempt to reduce speed in rough air and thus to reduce the loads due to a given gust. In setting up design criterions, however, no other assumption can be made until such time as transport pilots can be shown universally to reduce speed during periods of turbulence.

It is especially noteworthy that, for the present case, assuming what are believed to be reasonable values of λ_{cr} results in design load factors at V_L that closely approximate the values obtained by current methods.

Limitations

At the present time, no data are available to check the results of the analysis. When such data become available, it is possible that because of the limitations of the analysis, inconsistencies may be found in the results given herein. Three factors appear to be of particular significance, that is, average frequency, frequency distribution, and relative alleviation factor.

Average frequency.- The average frequency of $50/\bar{c}$ gusts per mile selected for the analysis is based on an average path ratio (ratio of length of flight path during which significant gusts are encountered to total length of flight path) of 0.1. The path ratio may be considerably affected by such items as airplane route (terrain), flight plan (altitude), and dispatching practice (prediction of adverse weather conditions with consequent detouring or "grounding" of flights), and is known to vary from 0.006 ($3/\bar{c}$ gusts per mile) to 0.24 ($120/\bar{c}$ gusts per mile). (See reference 1.)

As mentioned in the preceding discussion of the large transport-type airplane, the assumption has been made that the transport pilot make no attempt to reduce speed in rough air. This assumption makes it possible to use a single average value of gust frequency for all airspeed classifications. It is entirely possible, however, for the pilot to exercise his judgment and to fly at high speed only in smooth air and to reduce speed only during periods of turbulence. This procedure has the effect of reducing the path ratio for the high-speed classifications and, hence, of reducing the average frequency of gusts encountered; at the same time, the path ratios will be increased at the lower speeds with a consequent increase in average frequency. As a result, the required load factors at high speeds will be reduced over the values computed by neglecting pilot judgment; but at lowered speeds the reduction in required load factor due to reduction in speed tends to balance the increase in required load factor due to an increase in gust frequency and, hence, the maximum required load factors may not be greatly affected.

Frequency distribution of gusts.- The frequency distribution selected is actually the upper envelope of a number of individual frequency distributions. As a result, the selected frequency distribution will not necessarily correspond to any actual distribution and, consequently, exact correspondence between the results of this analysis and actual experience is highly improbable. In addition, the selection of a rational envelope distribution must necessarily contain the assumption that operating and dispatching practice remain reasonably constant. For example, if at some time in the future it becomes possible to predict - and thus to avoid - large gusts and if such avoidance is generally incorporated in operational practice, the frequency distribution of large gusts can then be expected to be correspondingly modified.

Another factor that might require consideration is that in very rough air the dual effect of pilot reactions and of airplane stability may result in an apparent change of frequency distribution. (See pp. 15 and 16 and fig. 4 of reference 1.) This apparent change in frequency distribution amounts to an increase in load factor per unit gust velocity and will depend on the characteristics of the particular airplane and on the technique used by the pilot.

Relative alleviation factor.- The relative alleviation factor K (fig. 1 of reference 1) neglects the effect of various airplane parameters. For specific airplanes the difference between the value of K given in figure 1 of reference 1 and the value of K as obtained by tests in gust tunnels may amount to as much as 20 percent. This difference may result in a discrepancy between computed and actual miles per critical gust of as much as 500 to 800 percent.

Utilization of analysis.- As previously mentioned, the data on hand are inadequate to permit the evaluation of the foregoing factors. Much more work will have to be done before the analysis can be considered reliable. The analysis, however, would appear to err on the conservative side and, hence, it can probably be safely utilized in cases for which current design requirements appear excessive, provided that adequate statistical data are available or that acceptable assumptions can be developed. When adequate statistical data become available and when a reasonable operational life can be defined, it should be possible to develop a more rational V-n diagram for gust load factors.

CONCLUSIONS

Statistical gust data analyzed in conjunction with assumptions concerning the proportion of time spent at various speeds indicated the following conclusions:

1. In the case of high-speed fighter-type airplanes, the application of a 30-foot-per-second gust at speeds up to the maximum

equivalent permissible gliding or diving speed appears to give design load factors that are unreasonably high in view of the small amount of time likely to be spent at such speeds.

2. The current civil design criterion of a 30-foot-per-second gust acting at the maximum equivalent airspeed in level flight yields values of design load factor that give reasonable operational life in terms of the analysis presented.

3. The current application of margins of safety to wing structure yields values of operational life, to complete structural failure, that depend upon the direction of the gust.

4. Variations in operational practice, as reflected by reduction of speed during periods of turbulence, possess a profound effect upon the structural integrity of the airplane.

5. Reasonable changes in speed-time distribution do not materially affect the results of the analysis presented.

6. Current design requirements may be made more rational at such time as adequate statistical data become available on gust frequency, length of flight path in rough air, and speed distribution.

Langley Memorial Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va., November 27, 1946

REFERENCE

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TABLE I.- SAMPLE CALCULATIONS OF DESIGN GUST CONDITIONS

FOR HIGH-SPEED FIGHTER-TYPE AIRPLANE

Pertinent dimensions and performance characteristics	Condition I	Condition II	Condition III
Required data			
Average life, L, miles	1,000,000	500,000	500,000
Number of allowable critical gusts in each speed bracket, d	5	5	5
Speed distribution, f_r, at			
$0.8V_L$	0.80	0.75	0.80
V_L	0.18	0.20	0.18
V_G	0.02	0.05	0.02
Mean wing chord, $\bar{c}$, feet	7.5	7.5	7.5
Wing loading, W/S, pounds per square foot	30	30	30
Slope of lift curve, m, per radian	4.6	4.6	4.6
Maximum gliding speed, V_G, miles per hour	625	625	625
Maximum speed in level flight, V_L, miles per hour	450	450	450
Results of sample calculations			
Spacing of critical gusts, miles, at			
$0.8V_L$	21,300	10,000	10,700
V_L	4,800	2,660	2,400
V_G	533	666	267
Critical gust velocity, feet per second at, $0.8V_L$	31.0	28.3	28.4
V_L	25.7	23.9	23.7
V_G	20.1	20.8	18.8
Load factors, g units, at			
$0.8V_L$	4.81 -2.81	4.47 -2.47	4.49 -2.49
V_L	5.31 -3.31	5.01 -3.01	4.98 -2.98
V_G	7.63 -5.63	7.86 -5.86	7.20 -5.20

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TABLE II.- SAMPLE CALCULATIONS OF DESIGN GUST CONDITIONS

FOR LIGHT BOMBER-TYPE AIRPLANE

Pertinent dimensions and performance characteristics	Condition IV	Condition V	Condition VI	Condition VII
Required data				
Average life, L, miles	1,000,000	5,000,000	1,000,000	1,000,000
Number of allowable critical gusts in each speed bracket, d	5	5	5	5
Speed distribution, f_r, at				
$0.8V_L$	0.85	0.85	0.75	0.85
V_L	0.14	0.14	0.24	0.14
V_G	0.01	0.01	0.01	0.01
Mean wing chord, $\bar{c}$, feet	9.68	9.68	9.68	9.68
Wing loading, W/S, pounds per square foot	44.0	44.0	44.0	22.0
Slope of lift curve, m, per radian	4.66	4.66	4.66	4.66
Maximum gliding speed, V_G, m per hour	348	348	348	348
Maximum speed in level flight, V_L, miles per hour	278	278	278	278
Results of sample calculations				
Spacing of critical gusts, miles, at				
$0.8V_L$	17,560	87,810	15,500	17,560
V_L	2,890	14,460	4,960	2,890
V_G	207	1,033	207	207
Critical gust velocity, feet per second, at $0.8V_L$	30.3	36.6	30.0	30.3
V_L	24.1	29.8	25.8	24.1
V_G	18.3	21.6	18.3	18.3
Load factors, g units, at				
$0.8V_L$	2.46 -.46	2.77 -.77	2.45 -.45	3.64 -1.64
V_L	2.46 -.46	2.80 -.80	2.56 -.56	3.64 -1.64
V_G	2.39 -.39	2.63 -.63	2.39 -.39	3.51 -1.51

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TABLE III.- SAMPLE CALCULATIONS OF DESIGN GUST CONDITIONS

FOR LARGE TRANSPORT-TYPE AIRPLANE

Pertinent dimensions and performance characteristics	Condition VIII	Condition IX	Condition X	Condition XI
Required data				
Average life, L, miles	5,000,000	15,000,000	5,000,000	5,000,000
Number of allowable critical gusts in each speed bracket, d	5	5	5	5
Speed distribution, f_r, at				
$0.8V_L$	0.85	0.85	0.75	0.94
V_L	0.14	0.14	0.24	0.05
V_G	0.01	0.01	0.01	0.01
Mean wing chord, $\bar{c}$, feet	13.7	13.7	13.7	13.7
Wing loading, W/S, pounds per square foot	28	28	28	28
Slope of lift curve, m, per radian	4.7	4.7	4.7	4.7
Maximum gliding speed, V_G, miles per hour	296	296	296	296
Maximum speed in level flight, V_L, miles per hour	222	222	222	222
Results of sample calculations				
Spacing of critical gusts, miles, at $0.8V_L$	62,000	186,000	54,800	68,600
V_L	10,200	30,600	17,500	3,650
V_G	730	2,190	730	730
Critical gust velocity, feet per second, at $0.8V_L$	35.2	38.7	34.7	35.5
V_L	28.4	32.4	30.2	24.9
V_G	20.9	23.4	20.9	20.9
Load factors, g units, at				
$0.8V_L$	3.02 -1.02	3.22 -1.22	2.99 -.99	3.04 -1.04
V_L	3.03 -1.03	3.32 -1.32	3.16 -1.16	2.78 -.78
V_G	3.00 -1.00	3.24 -1.24	3.00 -1.00	3.00 -1.00

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TABLE IV.- EFFECT OF SPEED ON CRITICAL GUST SPACING

[$\Delta n_L = 2.0$ at 30 fps]

Ratio of airplane speed to design level-flight speed, V_e/V_L	Critical gust spacing for limit load factor in either direction, $\lambda_{cr}/2$	Critical gust spacing for positive ultimate load factor, λ_{cr_p}	Critical gust spacing for negative ultimate load factor, λ_{cr_n}
1.0	0.15×10^5	110.0×10^5	2.2×10^5
.8	1.1	3,200.0	26.0
.667	9.0	110,000.0	280.0

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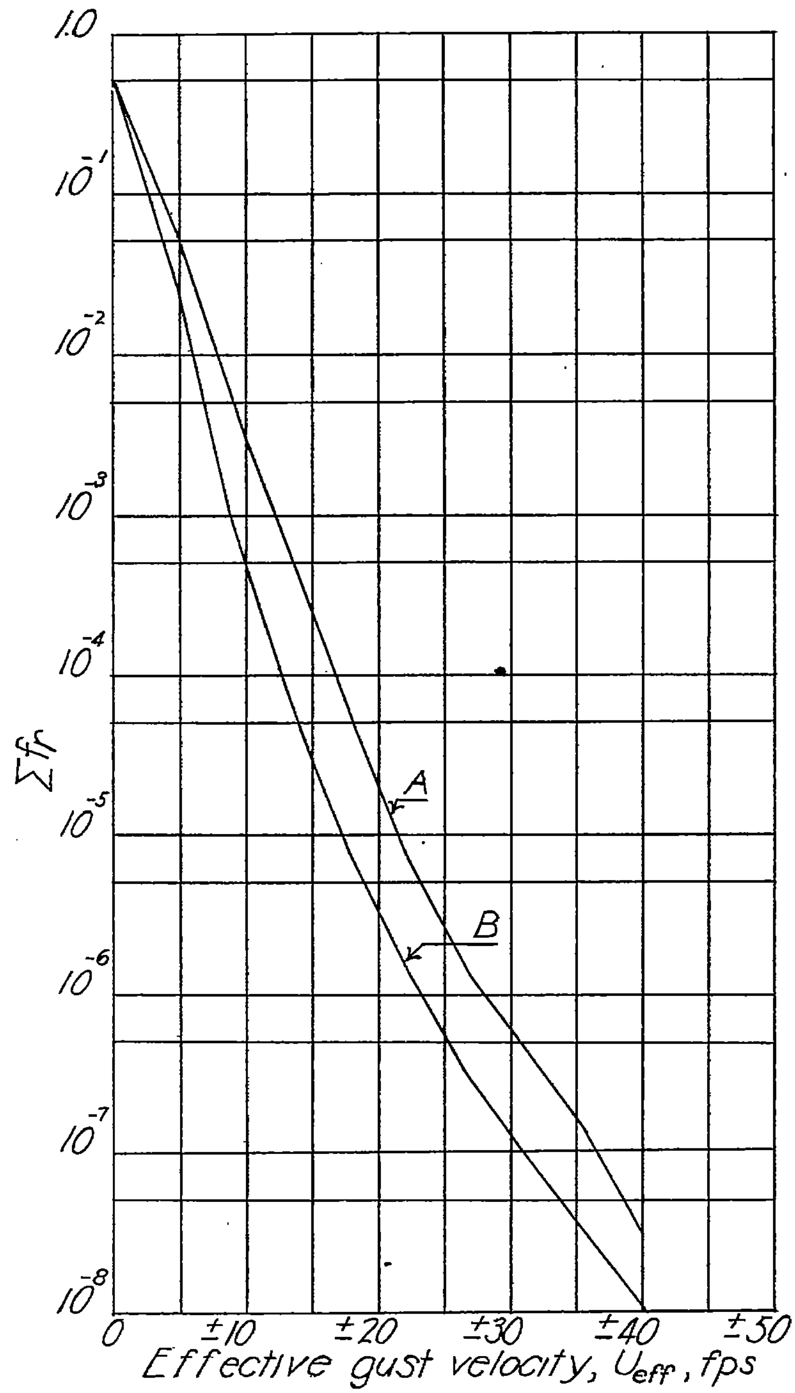

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Figure 1.- Unit summation curves defining approximate limits of samples. (From reference 1.)

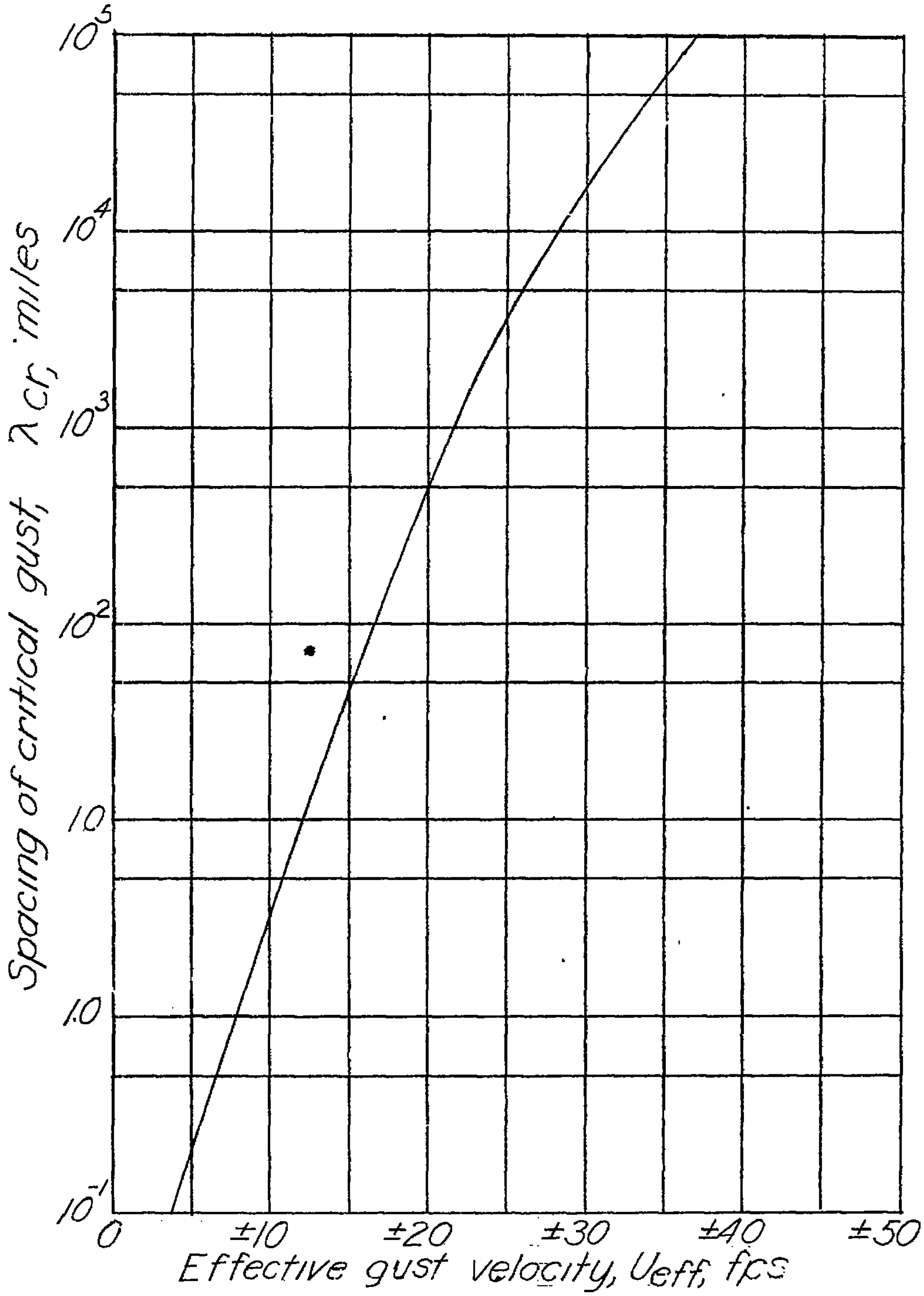

Figure 2.- Distance between gusts of intensities equal to or greater than selected values for airplanes with $\bar{c}$ = 1 foot. Average airline operating conditions.

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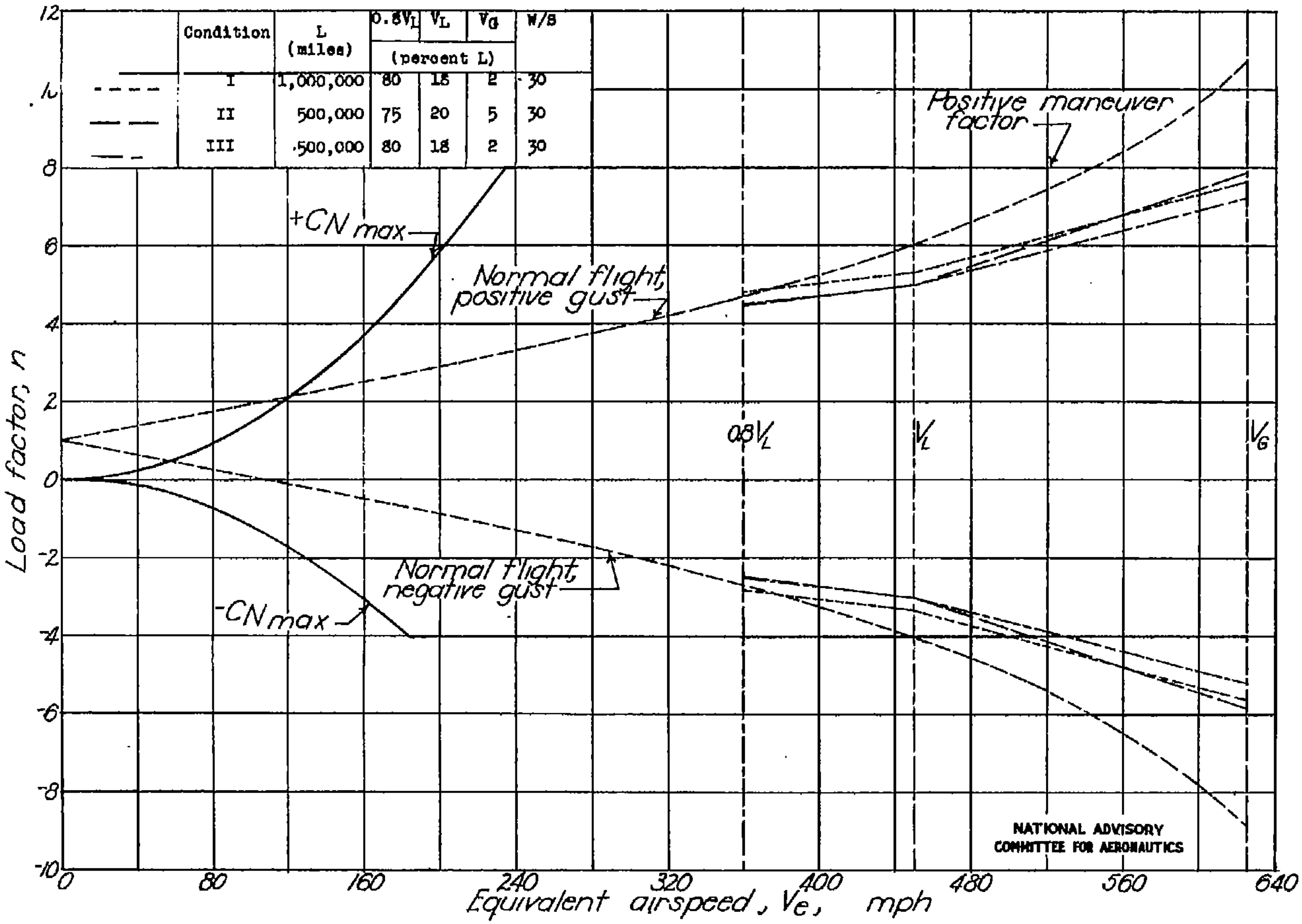
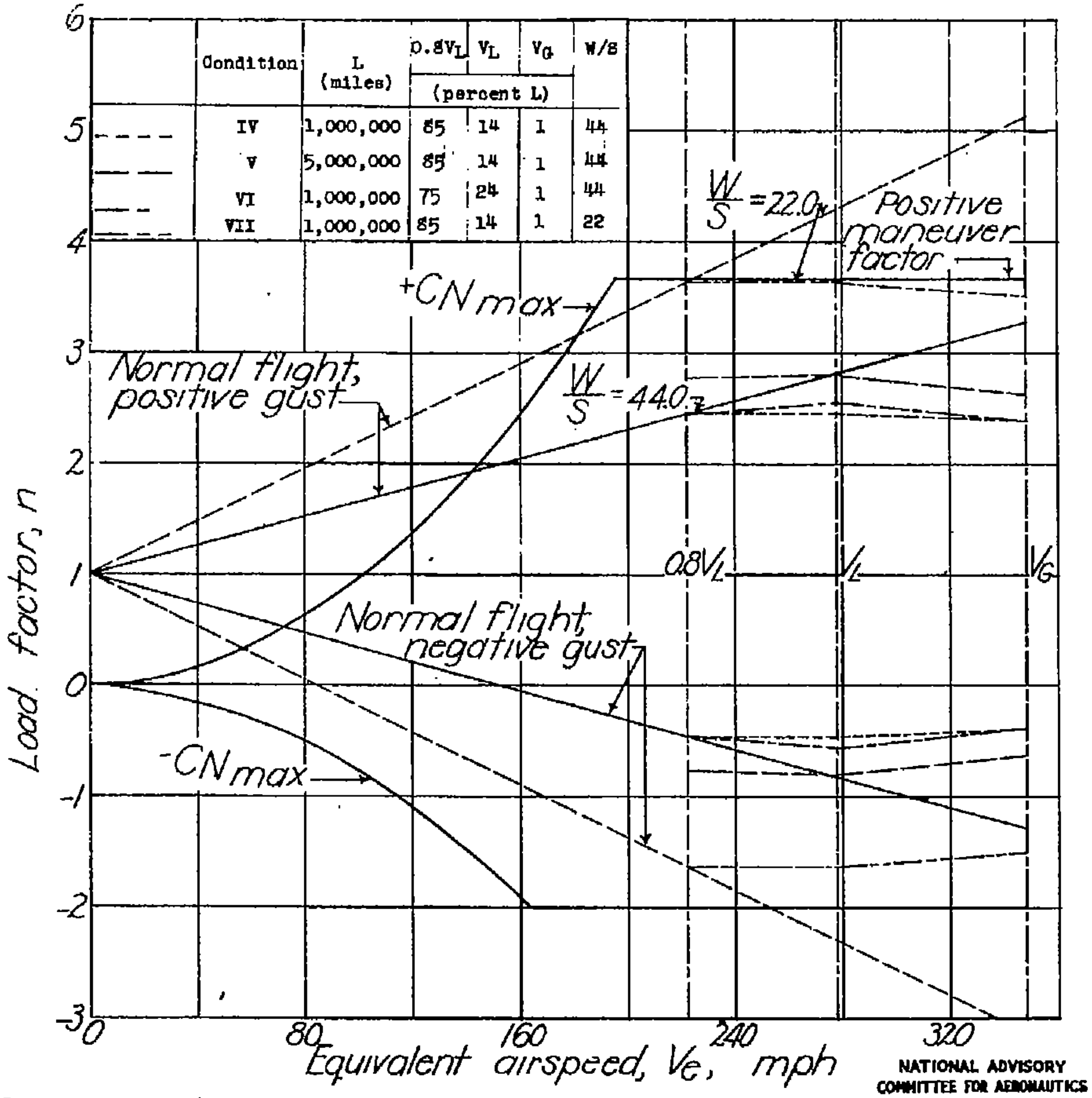
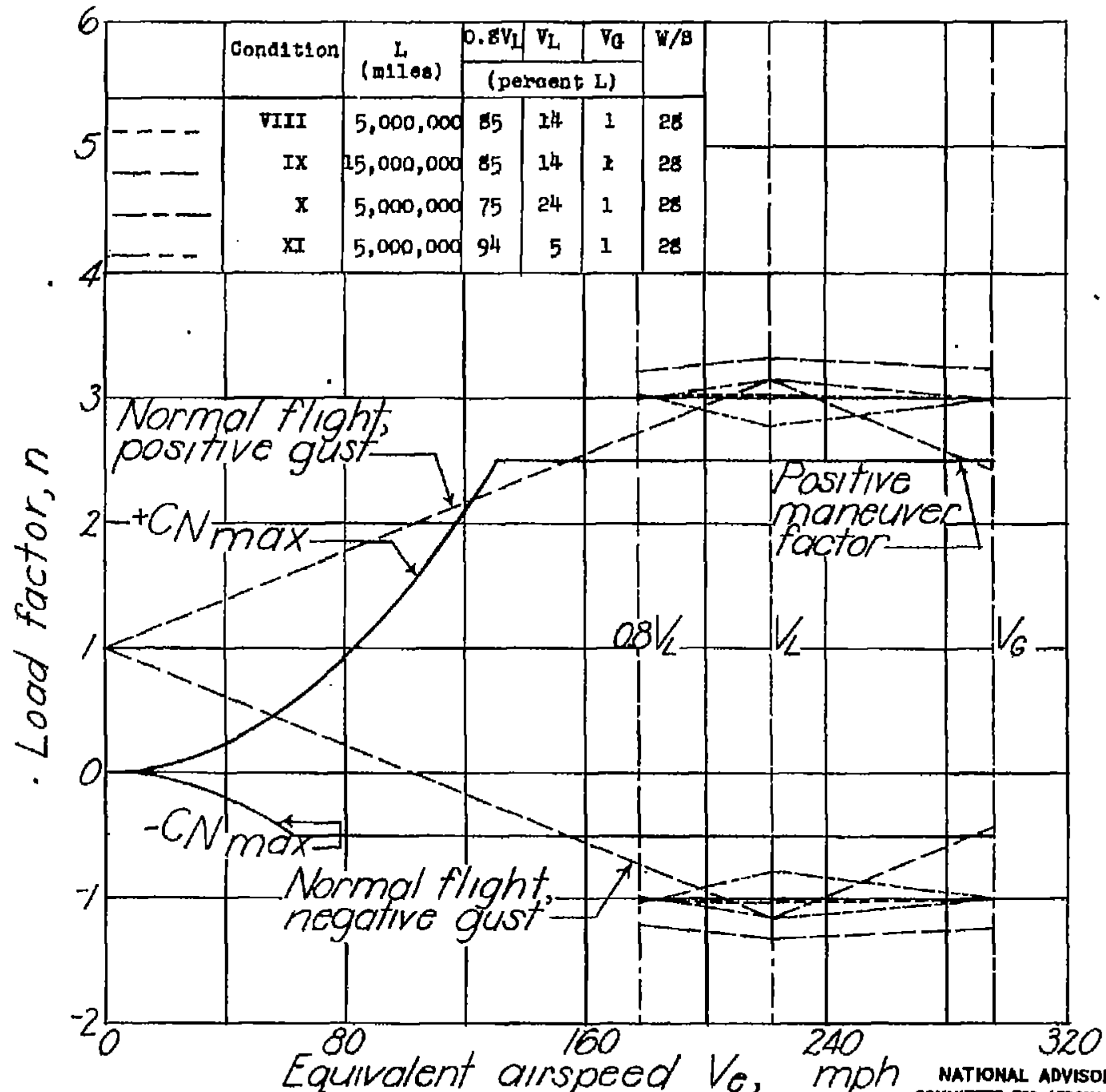


Figure 3.- V-n diagram of high-speed fighter-type airplane.



	Condition	L (miles)	$0.8V_L$	V_L	V_G	W/S
			(percent L)			
- - - -	IV	1,000,000	85	14	1	44
— —	V	5,000,000	85	14	1	44
— -	VI	1,000,000	75	24	1	44
— - -	VII	1,000,000	85	14	1	22

Figure 4.– V-n diagram of light bomber-type airplane.



	Condition	L (miles)	0.8V_L	V_L	V_G	W/S
			(percent L)			
----	VIII	5,000,000	85	14	1	28
— —	IX	15,000,000	85	14	1	28
——	X	5,000,000	75	24	1	28
— - -	XI	5,000,000	94	5	1	28

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Figure 5.- V-n diagram of large transport-type airplane.

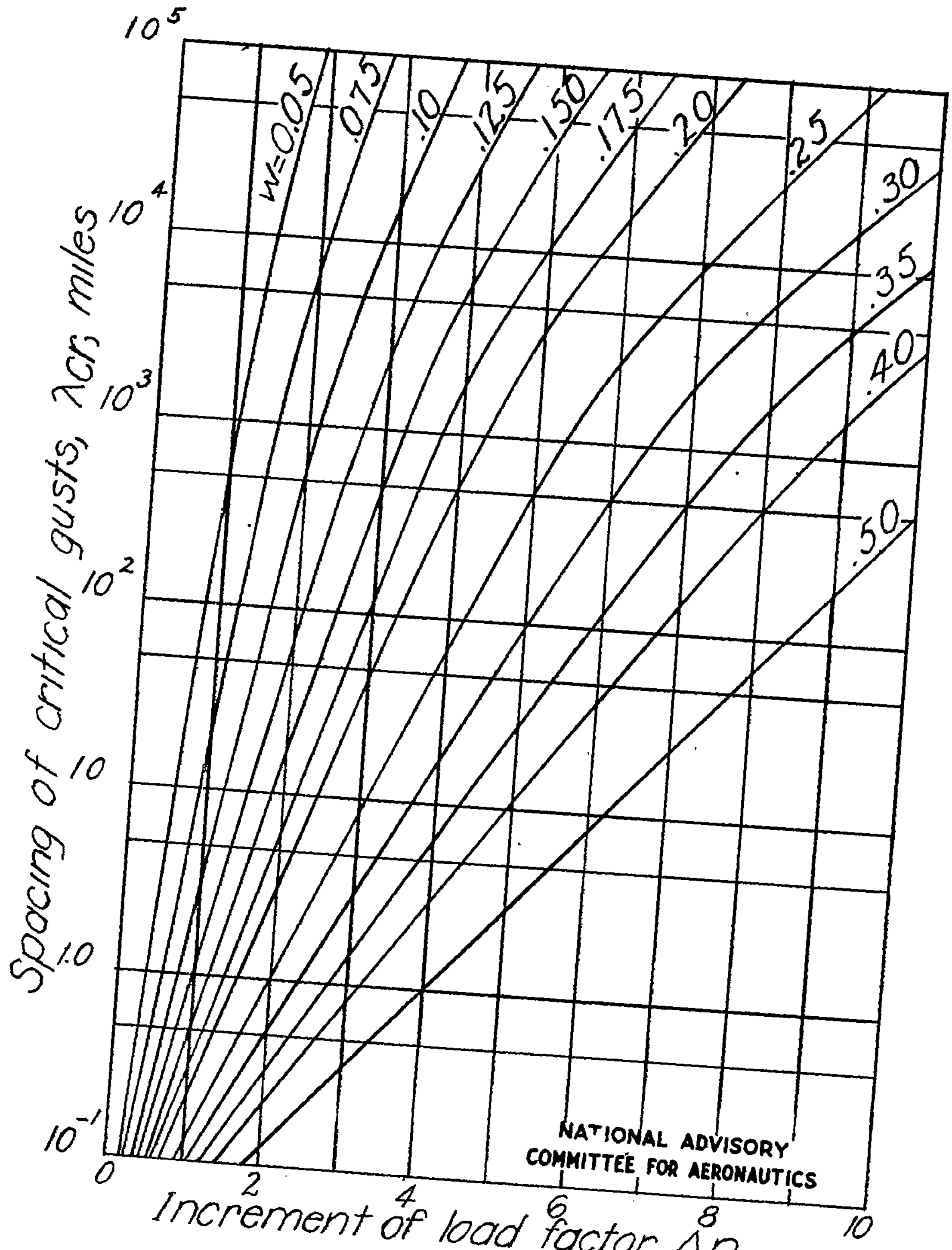

Figure 6.- Relation among λ_{cr}, w, and Δn.

$$w = 1.47 \rho_0 \frac{m V_e K S}{2W} = \frac{\Delta n}{U_{eff}}.$$

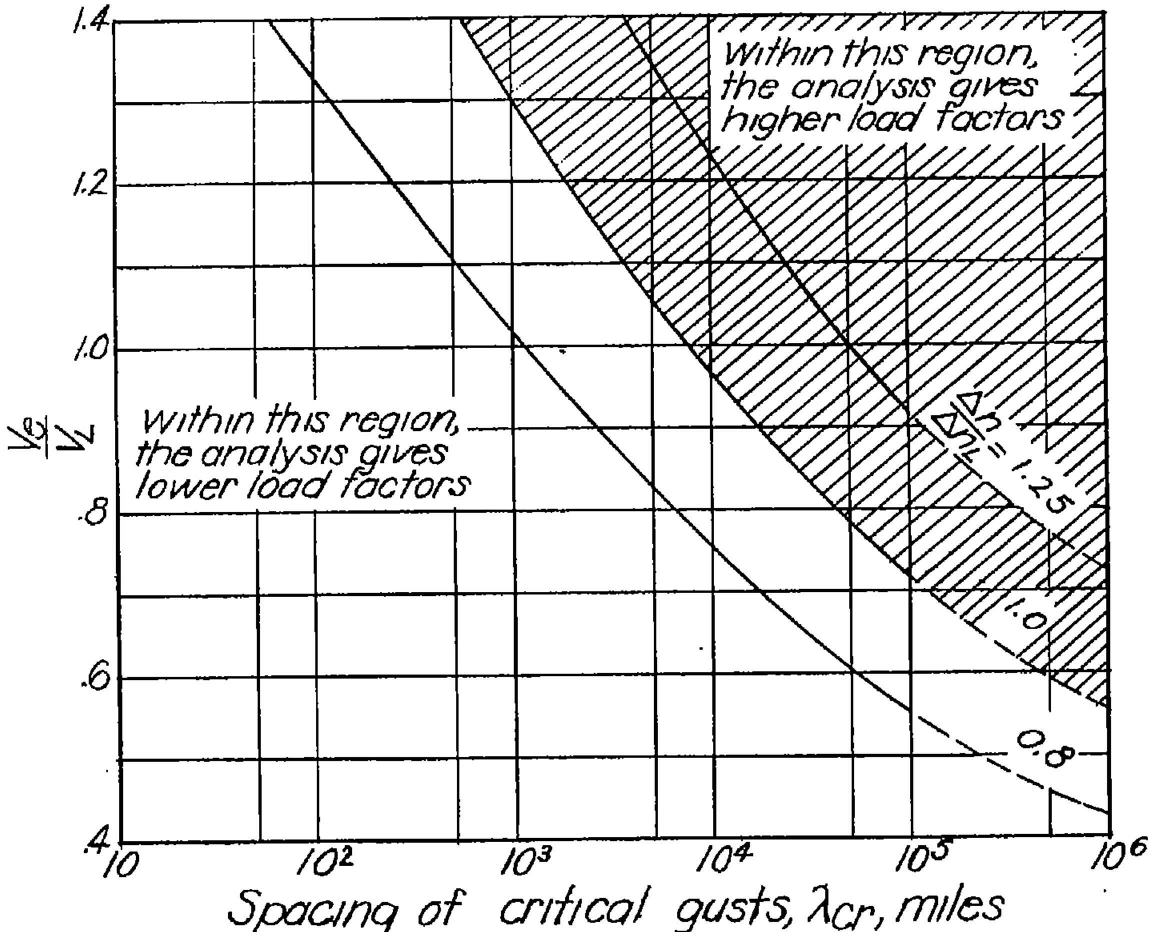

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Figure 7.– Range of parameters within which the analysis gives a lower load factor than a 30-foot-per-second gust acting at V_L.